CHAPTER 4

HYDROLOGIC ANALYSIS PROCEDURES

4-1. General.

Four hydrologic analysis procedures (and variations) are discussed herein and are classified as: (1) continuous record analysis methods, or (2) coincident frequency methods.

4-2. Basic Concepts.

a. The occurrence of fluctuating water levels both exterior and interior to the line-of-protection is the aspect that makes interior area analysis unique. Several terms are used to communicate information about the nature of these occurrences and they represent important basic concepts. If the exterior and interior occurrences are such that a consistent relationship exists one to the other (to some degree, one can be predicted from the other), the interior and exterior events are said to be correlated. If the physical and meteorologic processes of the interior and exterior events are related to one another, they are said to be dependent. If the situation occurs that the interior and exterior events produce stages that coincide, e.g., the exterior is high when an interior event occurs, then coincidence is said to occur. Coincidence can exist whether or not the interior and exterior occurrences are correlated or dependent.

b. At one extreme it is possible, though not likely, that there will be complete non-coincidence, i.e., the two occurrences will never coincide and thus interior and exterior water levels will never be high or low at the same time. The interior analysis could be performed without consideration of exterior conditions, thus greatly simplifying the problem. The occurrences could be correlated and dependent/or independent, but it would not be important to the analysis approach.

c. At the other extreme, it is possible, and somewhat more likely, that there will be complete coincidence, e.g., the two occurrences will always coincide so that high exterior levels are always present in the case of the occurrence of an interior event. The interior analysis can proceed without exterior analysis (by assuming blocked gravity outlets), since the conditions that exist for interior events are completely known. The occurrences would likely be correlated, although not necessarily dependent, but it would not be important to the analysis approach.

d. The situation for a given study will most likely lie between these two extremes. Analysis to determine the degree of correlation may help determine the likelihood of coincidence or independence but are not sufficient of themselves. Correlation studies are most useful for developing (if needed) a predictive capability. Formal study to determine the degree of independence is not possible at the present time, as it represents an unsolved technical problem area. To some degree, lack of correlation can suggest independence but is not sufficient of itself. More likely, the degree of dependence is determined based on inspection of the available record and judgements with regard to the meteorologic and physiographic origins of the interior and exterior events. It is important that the context be carefully defined; the fact that storms occur only in the winter (spring, etc.) is not an adequate basis for declaring that the occurrences are dependent. The critical focus must be on the aspects of the occurrences as they relate to possible coincidence, since this is the critical item with respect to analysis. The validity of the assumptions necessary for application of the coincident frequency method is controlled by whether or not independence is the case.

e. Inspection of the historic record is fundamental to determining important factors of correlation, independence, and coincidence. Establishing bounds on the consequences of decisions regarding these factors is an important analytic approach. It is generally helpful to analyze the two extremes of assuming complete and non-existent coincidence. Also, by determining the relative consequences of the assumption of independence, judgements regarding its importance to the study can be made. Within the framework of this information, the approach that will yield supportable conclusions will become more evident. Table 4.1 summarizes hydrologic analysis considerations for various levels of coincidence and dependency of interior and exterior conditions.

Table 4.1

Assessment of Coincidence
(Reference Paragraph 4-02)

COINCIDENCE	DEPENDENCE	EXAMPLES/COMMENTS	ANALYSIS CONSIDERATIONS
(HIGH)	(HIGH)	Hurricanes, large regional events; interior and exterior areas of similar magnitude.	Blocked gravity outlet conditions are common. Conventional hypothetical frequency analyses often appropriate for urban areas.
	(LOW)	Storm season of small interior area season coincides with snowmelt runoff of large basin.	Continuous record analysis methods or probabilistic approaches generally required. Gravity outlet is often blocked during critical interior events.
	(HIGH) (LOW)	This range of coincidence is most common. Relatively high likelihood of interior and exterior events occurring simultaneously.	Continuous record analysis or probabilistic methods generally required. Gravity outlets may be blocked during critical interior events.
	(HIGH)	Timing of interior and exterior events is such that they rarely coincide. May be affected by operation of upstream project.	Considerable study may be required to identify this condition and to assume its existence in the physical process. Coincident hydrology generally appropriate.
(LOW)	(LOW)	Rare condition. Interior flooding rarely if ever coincides with high exterior stages. Studies generally limited to gravity outlet assessments.	Coincident interior analysis is not necessary.

4-3 Procedure Overview.

a. General. Two basic hydrologic procedures for analyzing with and without interior project conditions are presented. These approaches are continuous record analysis methods, and coincident frequency methods.

b. Continuous Record Analysis Methods. Continuous record procedures can be subcategorized as:

(1) period-of-record (historic),

(2) discrete events of historic record, and

(3) stochastically generated continuous records.

Analysis of multiple discrete events are included as a continuous analysis method since events relating to coincident flooding of local runoff and river stages are identified from historic record of river stages, interior stages, and rainfall. Each of the three techniques may be used to develop hydrologic data of coincident flooding adjacent to the line-of-protection. Paragraphs 4-5, 4-6, and 4-7 describe the basic elements of the procedures.

c. Coincident Frequency Methods. Coincident frequency methods vary significantly in detail and procedures. The technique described herein develops a weighted frequency relationship from probabilities of exterior and coincident interior stage conditions. Section 4-8 describes the procedure in detail.

4-4. Hydrologic Data Requirements.

a. General. Hydrologic data required for analysis of interior areas include: topography, exterior stage data, historic rainfall records, runoff parameters, and seepage data. Physical characteristics and operation procedures for the without condition must also be determined.

b. Topography. Topographic data are required to define watershed and subbasin boundaries, runoff parameters (slopes, stream lengths), and estimation of elevation-area-storage relationships for natural detention areas. The availability of good topographic data as early in the study as possible is recommended.

c. Exterior Stage Data. Exterior stage data are required primarily at gravity and pumping station outlet locations. Secondary gravity outlet data may be aggregated (combined rating curves) to primary outlet locations, or ignored if the discharge capacity is insignificant relative to the primary outlets.

d. Rainfall Data. Rainfall data are required for interior and possibly for exterior areas analyses. The data should be basin average values for the study area, with weighted rainfall values determined where more than one rain gage is located within or near the watershed. If no rainfall gage exists in the basin, records from nearby rain gages will be used in the analysis.

e. Runoff Parameters. Hydrologic parameters affecting runoff are required for loss rates, runoff transforms, and base flow. Loss rate parameters may be initially estimated by using values from previous studies, or derived through analysis of measured rainfall and runoff volumes at gages. Loss rates are generally based on the land use antecedent soil moisture condition, and physical basin characteristics. Initial values for unit hydrograph and other runoff transform parameters may be estimated from land use and physical basin characteristics using published values or regression equations. The importance of volume rather than peak discharge in many studies permit use of simplified runoff methods to be employed with acceptable results. Calibration studies of assumptions, and verification of results to high water marks and frequency information must be performed as needed.

f. Physical and Operational Characteristics of Existing Measures. Information on physical and operational characteristics of existing flood loss reduction measures are normally required. Gravity outlet locations, capacity , and operation procedures are needed to enable simulation analysis to reproduce the historic record.

g. Other Data. Data on ponding areas, collection systems, and any hydraulic control effecting water movement are also often necessary.

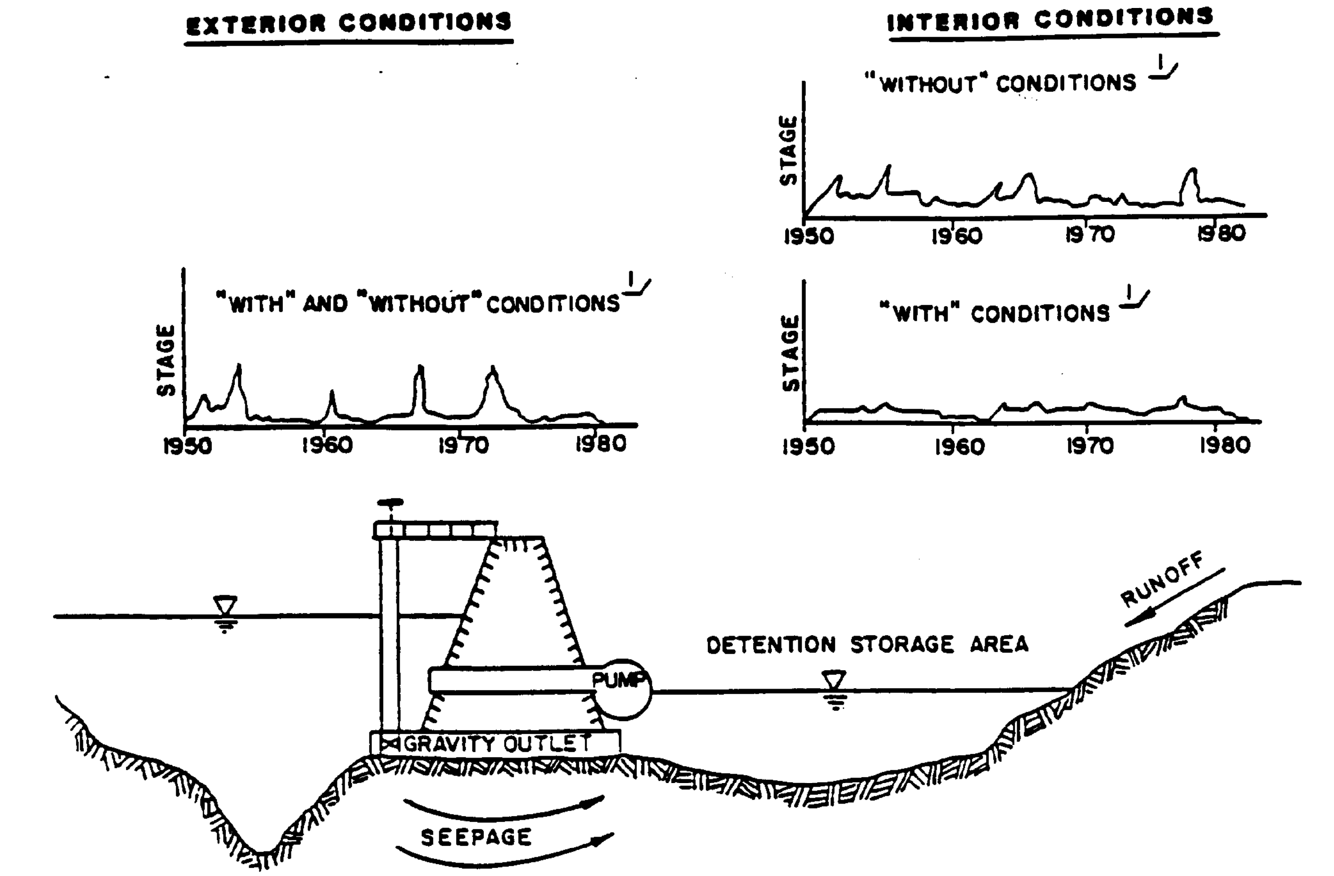
4-5. Period-of-Record Methods.

a. General. Period-of-record methods involve analysis of continuous historic records of hydrologic events. Analyses are performed for with and without conditions. The procedure consists of performing sequential hydrologic simulation of inflow, outflow, and change in storage to derive interior water surface elevations given exterior stages and interior runoff for the entire period-of-record.

b. Overview.

(1) An overview of the period-of-record methodology is depicted in Figure 4.1. Historic precipitation data typically are applied to subbasin loss rate, runoff transforms, and base flow parameters to yield runoff hydrographs at subbasin outlets. Hydrographs are combined and routed through the system (as appropriate) to gravity outlets and pumping stations to yield period-of-record inflows at the line-of-protection. These data are used with period-of-record exterior stage data to simulate the expected operation of the system. The results are period-of-record stage hydrographs at desired locations throughout the interior system. For urban areas, elevation-frequency functions are often derived for economic analyses. In agricultural crop areas, the stage hydrographs (stages and duration by season) are typically used to calculate crop damage directly.

(2) The period-of-record procedure is attractive because it preserves the seasonality, persistence, and dependence or independence of



1/ WITHOUT AND WITH CONDITIONS TIME TRACES OF STAGE ARE DEVELOPED FOR BASE, EXISTING, AND FUTURE CONDITIONS AS APPROPRIATE FOR INVESTIGATION.

FIGURE 4.1 Continuous Record Simulation: Period-of-Record Concepts

exterior (river) stages and interior flooding. The method enables the performance of the project to be displayed in a manner easily understood by the other study participants and the public. The procedure is particularly useful for evaluating crop damage of single subbasin watersheds (ponding adjacent to line-of-protection) in agricultural areas. System operational and maintenance costs may be calculated directly. The methods are generally tedious to apply because of the large amount of hydrologic data analyzed.

(3) Major considerations in application of the period-of-record procedures are the potential for the historic record being unrepresentative (records are usually short), and that the procedure requires significant information needs and extensive calibration. A short and unrepresentative historic record may yield inappropriate size and mix of measures and operation specifications of the system. The extensive data needs and model calibration requirements often result in a period-of-record analysis that is an unduly

simplistic rainfall-runoff analysis for single subbasins adjacent to the line-of protection. The level of detail is often adequate for agricultural areas, but may not be for the runoff-routing analyses required of complex urban areas.

(4) A variation of the period-of-record method is to analyze only those events from the historic record that are relevant to the interior analysis, thus reducing the number of specific events to be evaluated.

c. Hydrologic Analysis Procedures. The sequence of analytical procedures varys with individual studies and variations in period-of-record analysis methods. Figure 4.2 illustrates period-of-record concepts. A typical study sequence is provided below.

(1) Watershed and subbasin boundaries are delineated and damage reach index locations selected where hydrologic data are developed for flood damage analysis.

(2) Interior runoff for the period-of-record is developed using historic rainfall and adopted loss rates and runoff transforms by subbasins, and then combined and routed throughout the system.

(3) Other contributing interior flows such as seepage, wave overtopping, and overflow from adjacent areas are determined for use in the analysis.

(4) Interior inflow is routed through the system including the gravity outlets, pumping stations, and detention basins, adjacent to line-of-protection.

(5) The analysis model is calibrated based on initial results. Calibration may include: generation of period-of-record flows, volumes, and stages at gages; and calibration to historic high water marks, damage data, and frequency of overtopping roads and bridges. Adjustments may be made to loss rate and runoff transform parameters, seepage functions, antecedent moisture accounting techniques, and operation procedural assumptions.

(6) Develop elevation-frequency relationships, duration of flooding, and other pertinent hydrologic information at locations of interest for the existing without conditions.

(7) Repeat steps 2, 3, 4, and 6 for future without conditions and future with conditions for each to the proposed alternative plans.

4-6. Multiple Discrete Event Method.

a. The multiple discrete event procedure is based on development of interior stage-frequency functions for areas affected by coincident flooding. The procedure generates a composite stage-frequency function from analysis of two conditions. The first involves analysis of selected (high stage) exterior events of historic record that have an effect on interior flooding when interior rainfall occurs coincidently. The second condition involves analyses

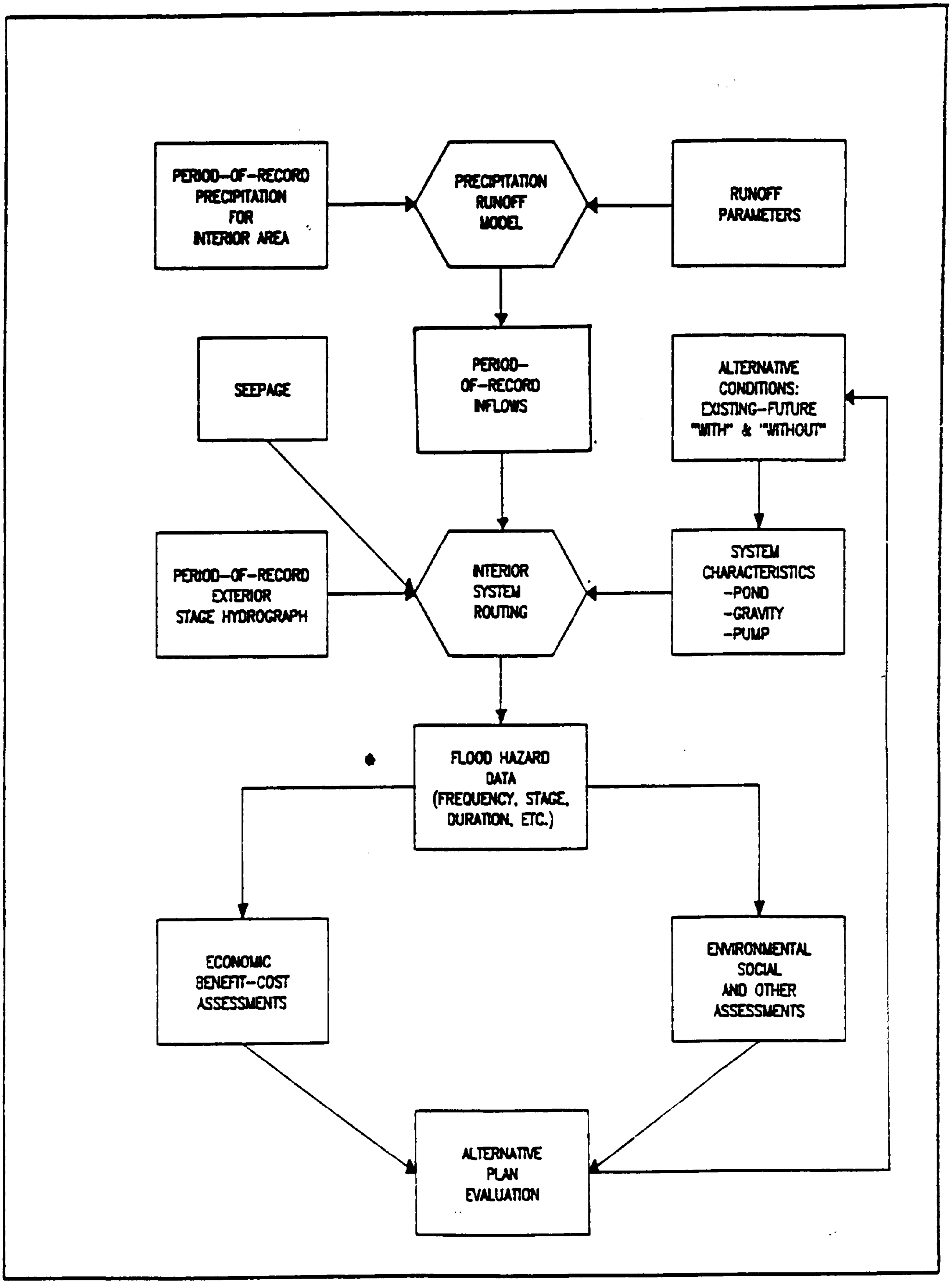
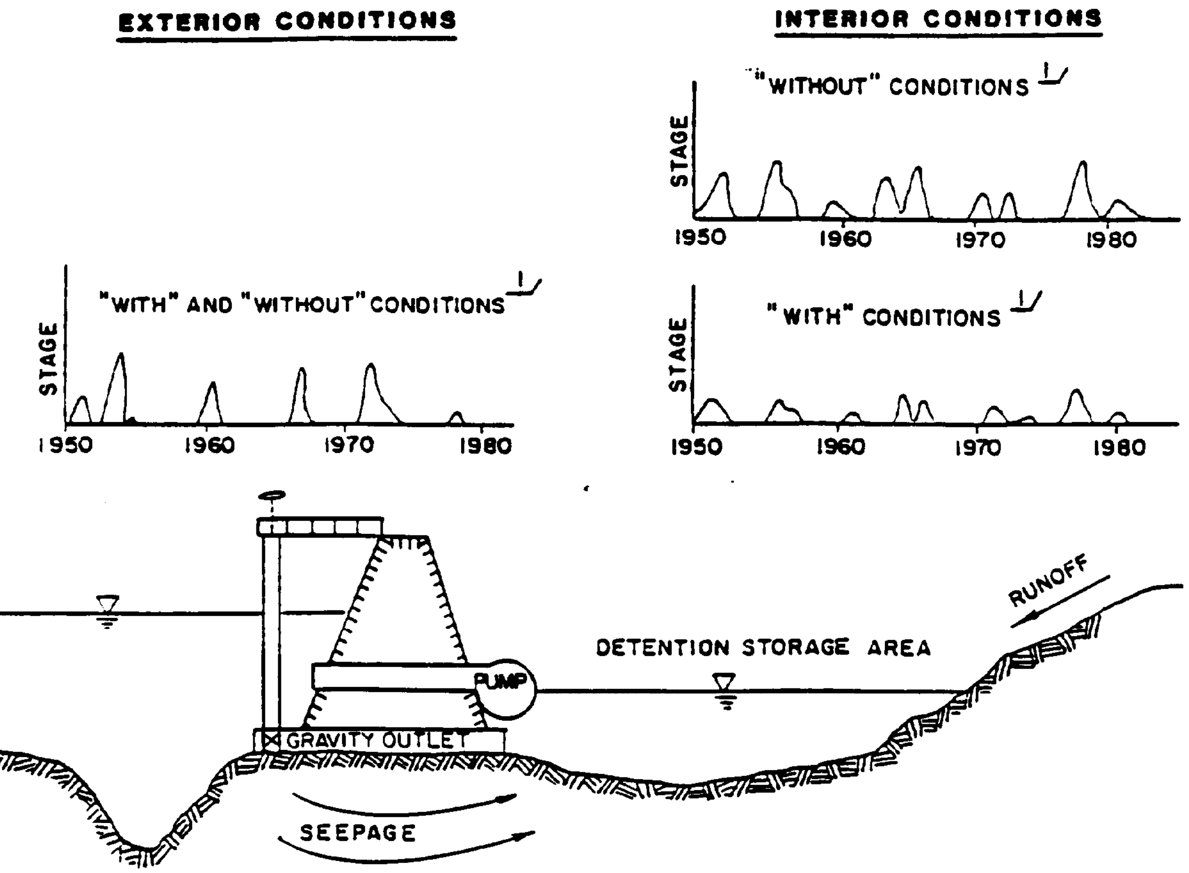


FIGURE 4.2 Period-of-Record Analysis Schematic

of low exterior stages associated with interior flood analysis generated by either coincident historic rainfall or hypothetical frequency storm events. For the second condition, historic rainfall is commonly used in agricultural areas and hypothetical frequency rainfall for analysis of urban areas. The result is a stage-frequency function for each of the two conditions. They are then combined into a composite function by the application of the joint probability theorem. Figure 4.3 conceptualizes the analysis process.



1 WITHOUT AND WITH CONDITIONS TIME TRACES OF STAGE (BASED ON SIGNIFICANT EVENTS) ARE DEVELOPED FOR BASE, EXISTING, AND FUTURE CONDITIONS. HYPOTHETICAL FREQUENCY ANALYSIS OF INTERIOR (NOT ILLUSTRATED) MAY BE PERFORMED FOR LOW EXTERIOR STAGES.

FIGURE 4.3 Continuous Record Simulation: Discrete Events

b. The multiple discrete event method is similar to the period-of-record procedure in that the concepts of coincident flood simulation are easy to understand and antecedent moisture conditions are accountable. Both methods may be influenced by short and unrepresentative historic records. The two procedures are different in that the discrete event analysis evaluates fewer events, uses fewer parameters, and generally is more applicable for complex hydrologic systems. Combining probability functions is a distinct departure as well. The discrete event method may miss events that impact on the results, and does result in a less automated process of analysis than the period-of-record.

c. Hydrologic Analysis Procedures.

(1). The hydrologic procedures typically applied to perform multiple discrete analyses of interior areas are shown in Figure 4.4.

(2) The historic record of exterior stages is reviewed to determine the events which may have an impact on interior flooding. Dividing the record by season may be an important consideration. Unless seepage or overflow from adjacent areas or wave overtopping are significant problems, events must occur coincidently with interior events that result in damage when the gravity outlets are closed. The event definition should identify dates, be of sufficient length to determine duration and seasonal effects on the damage potential, and assess antecedent moisture conditions.

(3) Rainfall-runoff and interior routing procedures for blocked gravity outlet conditions are similar to those described for period-of-record, except evaluations are performed for single historic events. Historic rainfall data must be coincident with the exterior events selected for the analysis. Rainfall excess is applied to runoff transforms and routed to produce hydrographs throughout the interior system. Seepage and other inflow functions are developed. Total hydrographs are subsequently routed through existing gravity outlets and pumping stations. The gravity outlets are blocked until a positive differential head exists between the interior and exterior.

(4) Stage-frequency functions are developed for gravity conditions (see paragraph 1-2). The events are normally ranked in decreasing order and plotting positions established based on the historic record or hypothetical events as appropriate. The order assignments of the individual events may change with location in the system and adjustments to hydrographs resulting from physical works.

(5) Analysis of gravity conditions normally use hypothetical frequency storm and runoff analyses for urban areas and historic events for agricultural crop damage assessments. If historic events are used, maximum intensity rainfall is selected from continuous records for the period coincident with low exterior stage or unblocked gravity outlet conditions.

(6) Rainfall-runoff analyses are performed for the events and stage-frequency functions developed for desired locations. Events are routed through the line-of-protection assuming low exterior stage conditions.

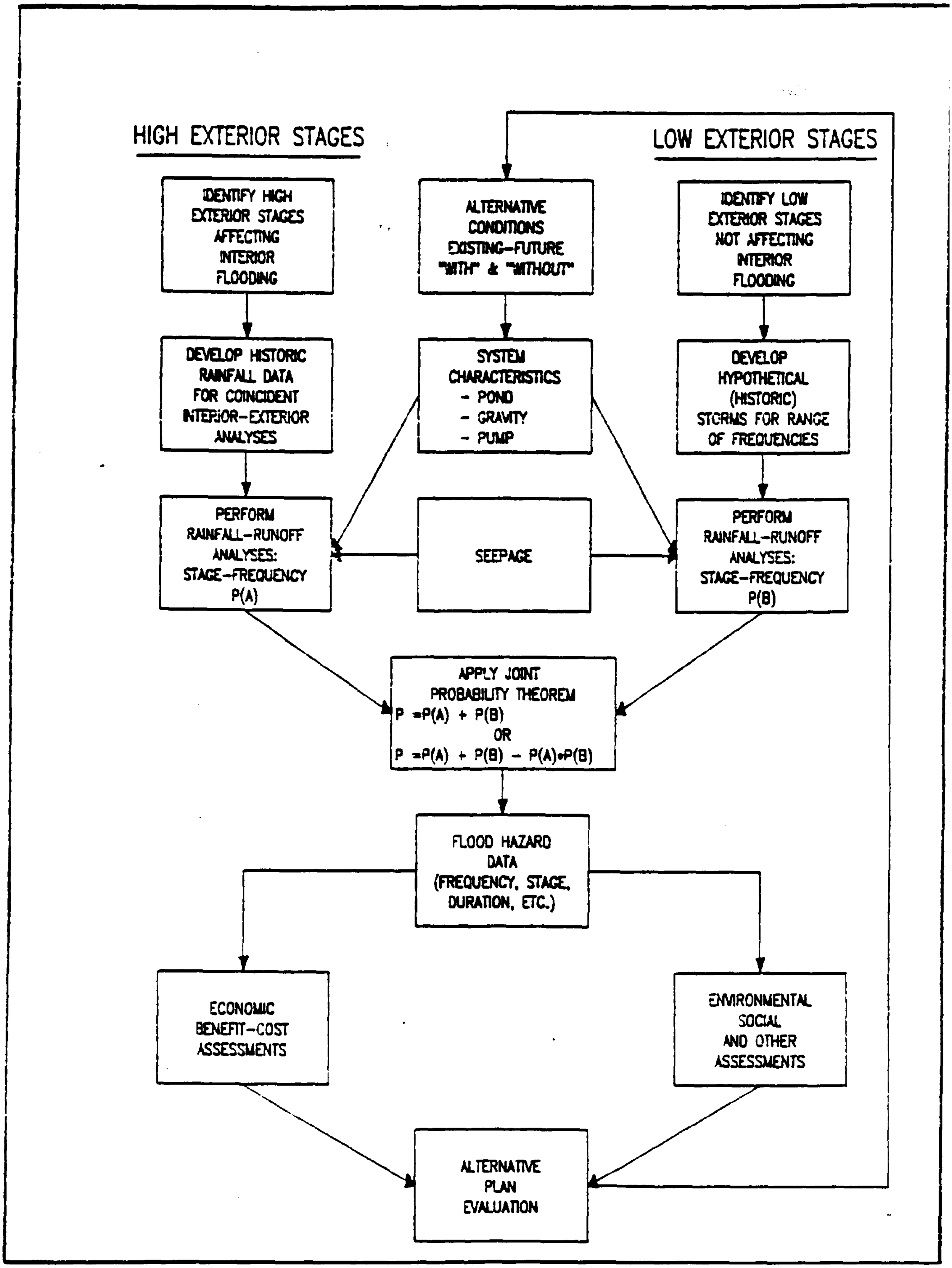


FIGURE 4.4 Discrete Event Analysis Schematic

Elevation-frequency relationships are developed at desired locations. If hypothetical frequency storms are used, the frequency functions are developed directly from the recurrence functions. For historic storms, the events are ranked and plotting positions assigned.

(7) The joint probability theorem is used to combine the frequency functions for blocked and unblocked gravity outlet conditions. For annual series, for a given stage (or flow) total probability is equal to the sum of the probability at that stage (or flow) for each relationship minus the product of their individual probabilities (to subtract probability of events occuring in the same year). For partial series (with multiple events in a year assumed to cause damage) the total probability is the sum of the two (blocked and unblocked) probability relationships.

4-7. Stochastic Simulation Procedure.

a. Conceptually, the technique of stochastic hydrology provides the means for overcoming the limitations of analysis of historical events. Stochastic hydrology techniques can provide sequences of statistically-likely hydrologic events, including combinations of interior and exterior events that may be rarer than any yet observed. If a number of such sequences can be used for the required analyses, the operation policies or design should be more resilient than those biased towards control of a specific design event. Even when a specific design event or historical sequence is employed, analysis of system response to the synthetic sequences can demonstrate the sensitivity of design or operation policies to the flow sequence.

b. Practical, tested stochastic hydrology procedures have not been widely used for analyses required for interior flood control studies. A number of synthetic streamflow generation models are in use that generate sequences of monthly, seasonal, or annual flows. However, the primary need for interior drainage studies is for sequences of daily or hourly flows. Operational models that generate such sequences are not now readily available. Generation of synthetic precipitation events analyzed with a rainfall-runoff model to develop the required sequences is an alternative approach; and, operational tools to accomplish this have been tested in an experimental mode. Ongoing research may ultimately provide practical stochastic simulation methods. Analysts should be alert to opportunities to apply such technology as it becomes more accepted and applicable for continuous record type of analyses. Figure 4.5 presents a conceptualization of applications of stochastic simulation procedures.

4-8. Coincident Frequency Methods.

a. Overview. Coincident frequency is one of several probabilistic methods that can be used to perform interior area analysis. Coincident frequency methods for performing hydrologic analyses of interior areas normally apply the total probability theorem to generate stage-frequency functions for interior areas affected by coincident interior and exterior flooding. The procedure is directly applicable to areas where occurrence of the exterior and interior events are independent. These areas often include

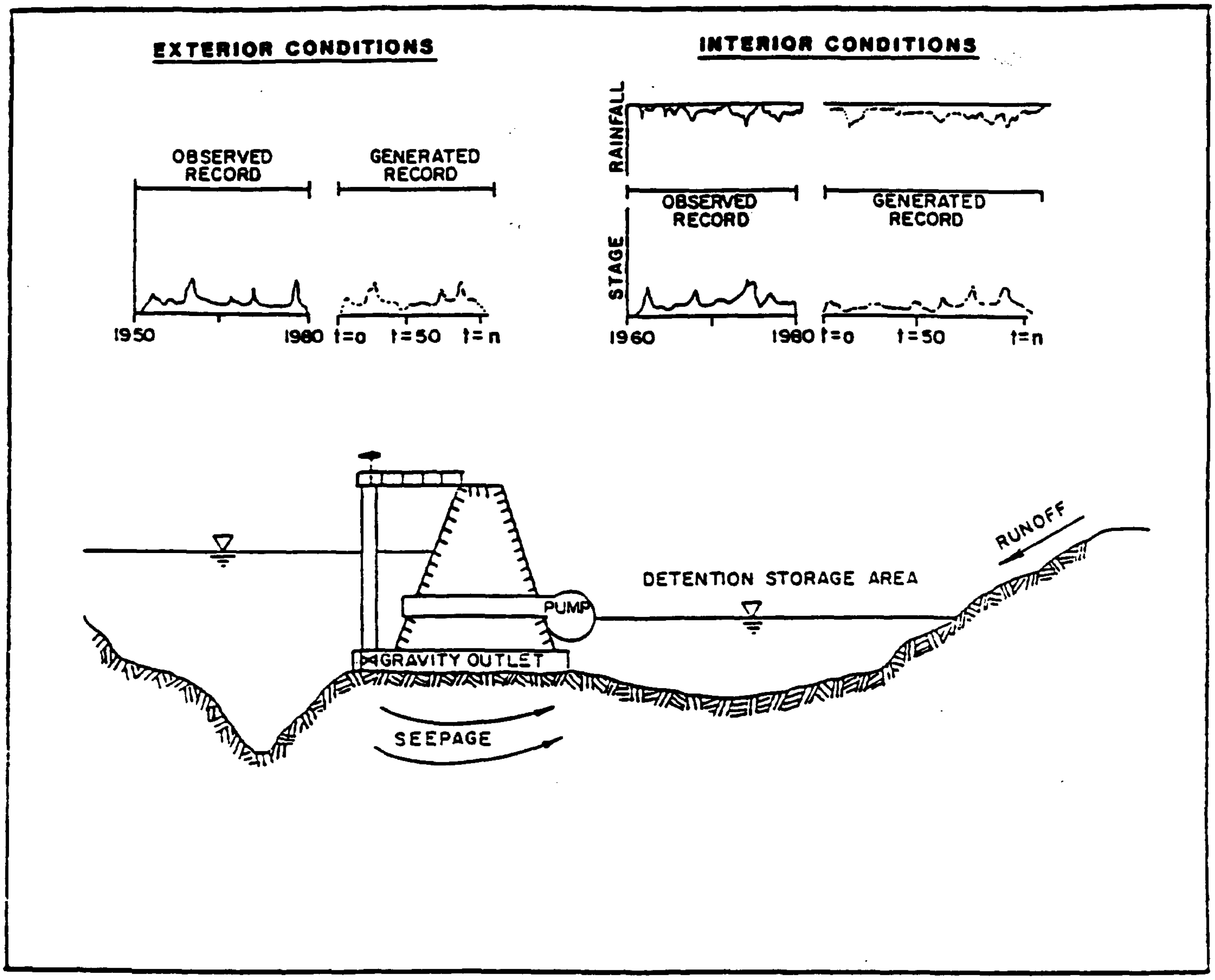


FIGURE 4.5 Continuous Record Simulation: Stochastic Concepts

relatively small interior areas located along large rivers, lakes, or coast lines. Variations in the procedures presented may be used to perform similar assessments of dependent interior and exterior event occurrences based on particular study conditions and data availability. Figure 4.6 depicts the general concepts.

b. Computation Method.

(1) The coincident frequency approach utilizes a series of hypothetical single event hydrographs for the interior analysis and stage-duration (stage versus percent of time exceeded) for exterior stages. The methods are applied for detention storage levels adjacent to the line-of-protection. Basic steps in the approach are defined below and depicted in Figure 4.7.

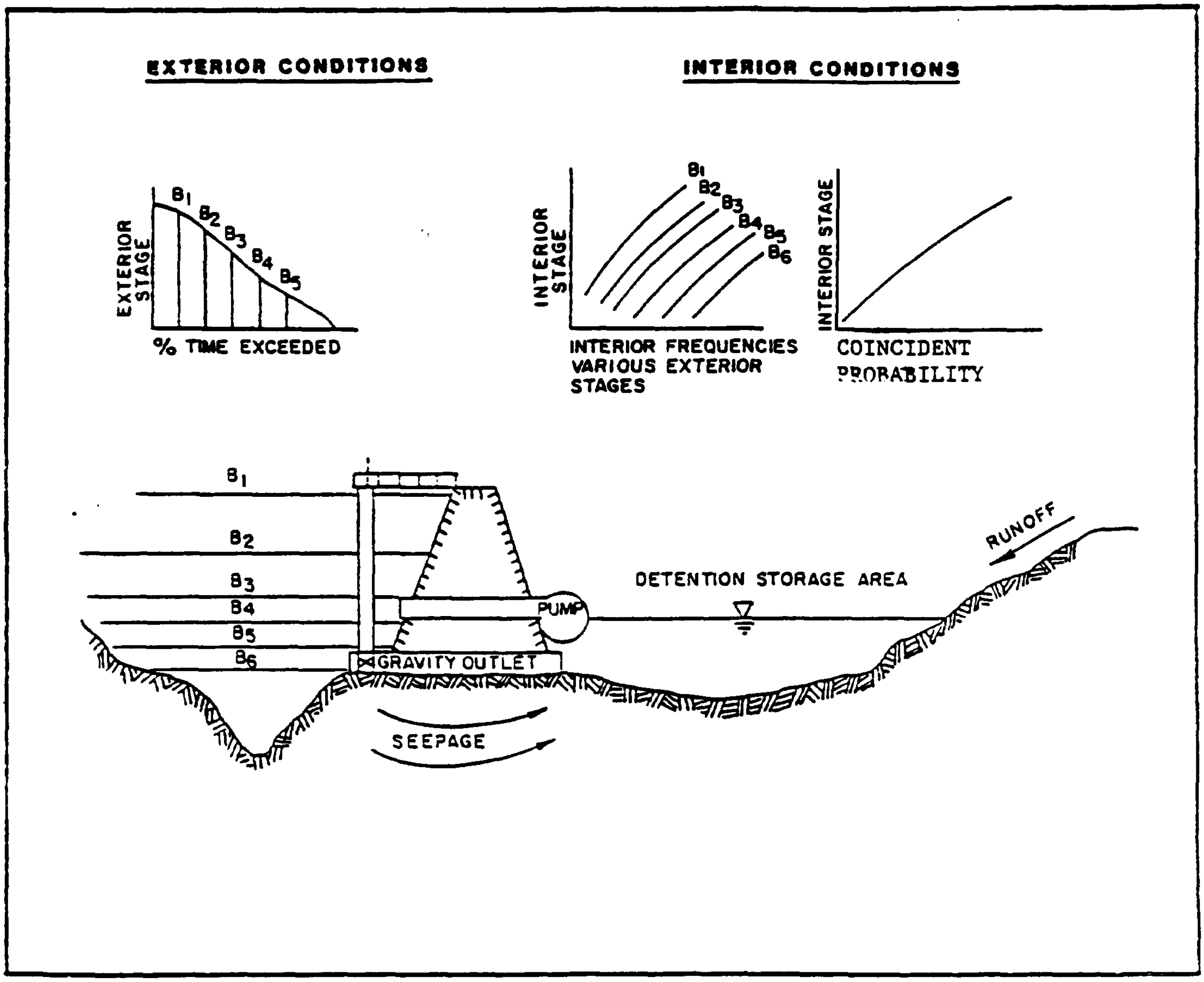


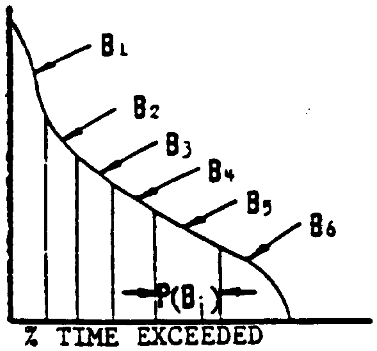
FIGURE 4.6 Coincident Frequency Concepts

Step 1. A stage-duration function is developed for exterior stages and divided into appropriate segments. The middle value of each segment is takenas an index river stage. The segment interval, $P(B_1)$, for the duration represents the probability of the interval. The sum of the probabilities must equal 1, i.e., $\sum P(B_i) = 1$.

Step 2. A series of hypothetical frequency events are analyzed for each of the exterior tailwater conditions. A stage-frequency $(P(A/B_i)$ function is developed for each exterior tailwater condition.

Step 3. The coincident detention elevation (at the outlet) vs. exceedence probability functions are developed from the conditional probability curves using the total probability theorem, where:

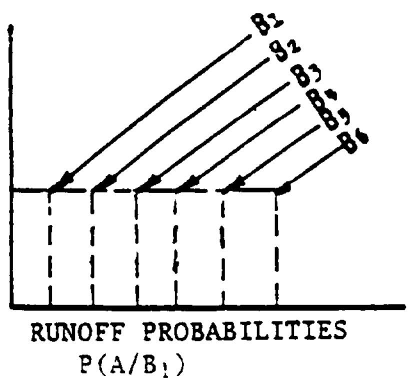
STEP 1



Develop duration (% time exceeded) functions for exterior conditions, where:

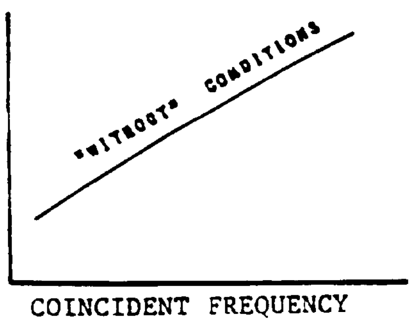
$$\sum_{i=1}^{n} P(B_i)=1$$

STEP 2



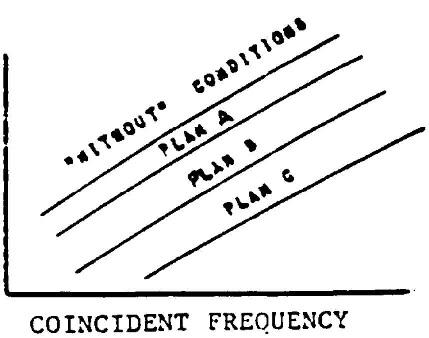
Analyze range of hypothetical interior runoff events for various frequencies and stage levels.

STEP 3



Develop weighted (coincident) probability functions for "without" condition.

STEP 4



Redo steps 2 and 3 for each alternative affecting stage - frequency relationships of interior areas adjacent to line-of-protection

FIGURE 4.7 Coincident Frequency Procedures

$$P(A) = \sum_{i=1}^{n} (P(A/Bi) \times P(B_i))$$

where: $P(A)$ = probability of exceeding a given interior ponding elevation
$P(B_i)$ = probability river is at the specific stage interval (i), where i assumes full range of values which have affect on pond elevation.
$P(A/B_i)$ = probability of exceeding a given pond elevation if the river stage is at the stage interval described in step 1.

Step 4. Steps 2 and 3 are repeated for each alternative of gravity outlet and pumping stations analyzed.

(2) The coincident frequency methods typically require less data than continuous record techniques. In general, the procedure is easier to apply and calibrate for urban interior analyses than methods involving continuous record simulation. Use of hypothetical frequency hydrographs (peak, volume, and all durations are statistically consistent with the percent chance exceedance assignment of the event) reduces the chance for nonrepresentative results that might occur from procedures using historic records. Seasonal analyses aspects for agricultural or other such analyses may be performed by generating and weighting the information by seasons and weighting appropriately to obtain annual values. However, in practice, these procedures have not been fully developed and are less direct than from continuous record simulation methods.

(3) The coincident frequency concepts for analyzing interior areas are more difficult to explain (in lay terms) and understand than period-of-record concepts. The assumption of independence of events may not be valid. Also, the method does not provide direct means for estimating operational costs and impacts of damage resulting from timing and duration of flooding that, for example, might be important in evaluating agricultural crop damage.

c. Analysis Procedures.

(1) Overview. The analytical procedures using the coincident frequency methods vary with individual studies. Figure 4.8 illustrates the general analysis process.

(2) Delineation of Area. Delineate watershed subbasin boundaries and establish damage reach index locations where hydrologic data (discharge or elevation-frequency functions) are required.

(3) Exterior Stage Data. Develop stage-duration (percent of time stage is exceeded) relationships at primary outlet locations. The relationships are typically developed using historic gaged data. The data are often transferred from a nearby gage. Adjustments may be needed if exterior stage differences between the gage location and study location are significant.

(4) Rainfall-Runoff Analysis. Rainfall-runoff analysis of the interior area is performed to generate stage-frequency relationships at

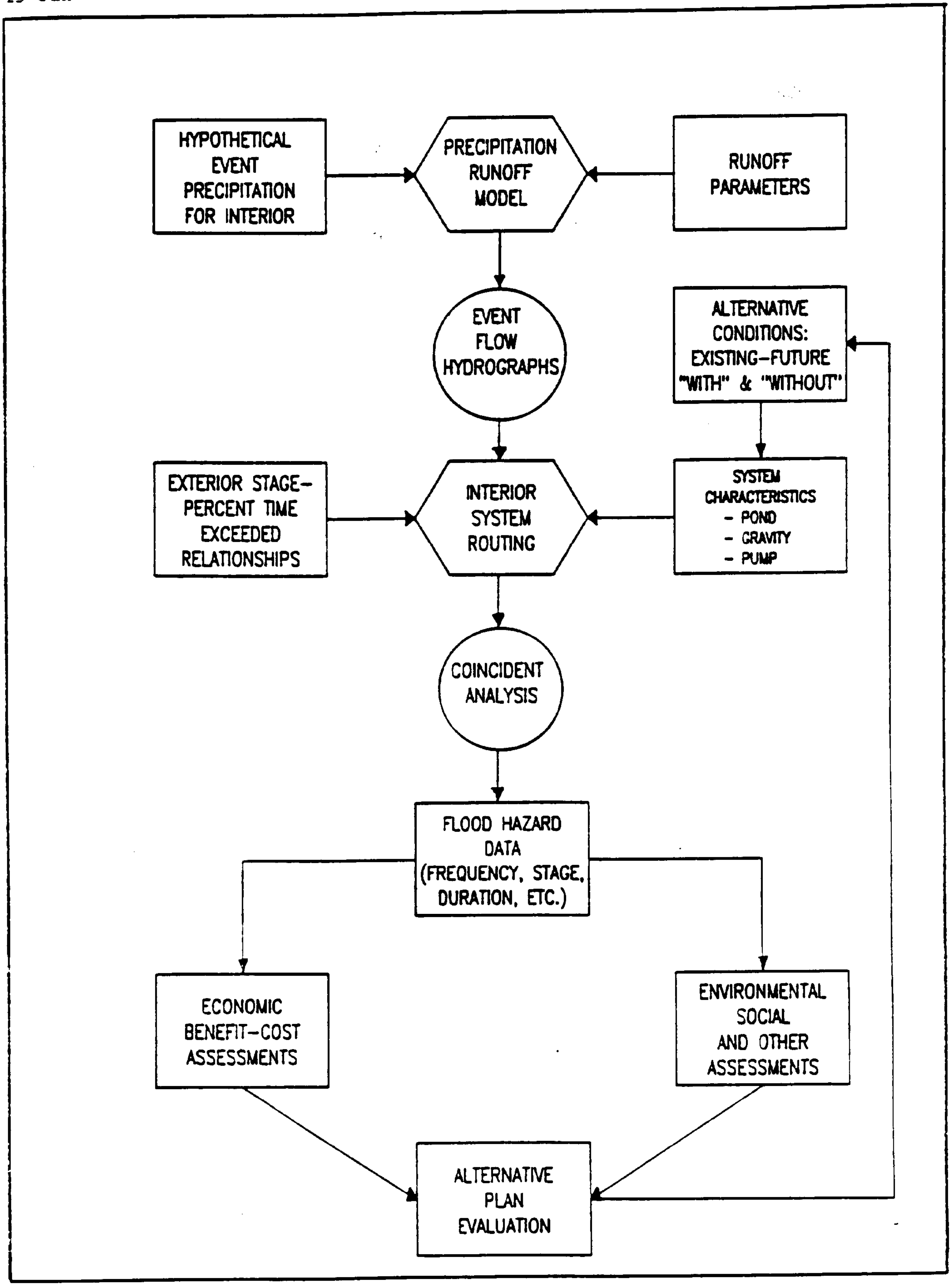


FIGURE 4.8 Coincident Frequency Analysis Schematic

desired locations. Hypothetical frequency storms are developed and applied to loss rate functions to obtain rainfall excess. The excess is applied to runoff transforms to produce runoff hydrographs which are subsequently combined and routed throughout the system. The results may be calibrated to observed events, flood damage information, or other items such as frequency of overtopping of roads and bridges.

(5) Stage-Frequency Functions. Stage-frequency functions are developed conventionally at interior locations not affected by the coincident interior flooding. For areas affected by coincident flooding (adjacent to the line-of-protection), the coincident frequency weighting method as previously defined and depicted in Figures 4.6 and 4.7 is applied to generate the stage-frequency relationship.

(6) Iteration of Alternative Plans. Repeat steps (4) and (5) for future without conditions and for each of the alternative plans. The results, along with the existing without conditions, are interfaced with evaluations performed by other study elements.

4-9. Procedure Selection.

a. The selection of procedures for hydrologic analyses of interior flooding is dependent upon the relationship of several factors, such as the nature of the study, characteristics of the study area, local institutional policies and practices, and experience of the analyst.

(1) Several of these factors are interrelated in that there is generally a relationship between the type of study and complexity of the physical system. Items of institutional policies and professional staff experience are often the overriding factors. It is also important to acknowledge that the several methods may be applied with varying amounts and accuracy of data so that it is possible to tailor the procedures to the stage of an investigation.

(2) Studies that seek general feature answers (e.g., early stages of Survey feasibility studies) for simple systems without complex coincident flooding may use conventional event analysis approaches. As the complexity of the coincidental aspects increased, the methods generally described herein become important. Where coincident events are clearly independent and the system is simple, the coincident frequency method is likely to be acceptable and more efficient for early to mid-stage planning investigations. Where coincident events are found to be less than completely independent, the continuous record simulation methods of period-of-record and discrete event analysis are generally acceptable methods. The multiple discrete events method is normally more adaptable to complex interior physical systems than is the commonly applied period-of-record. Although presently untested in interior analysis settings, the stochastic class of methods provides an opportunity to analyze simple systems where the historic record is short and/or there is need to evaluate operational strategies for several alternative hydrologic sequences other than those observed. As studies progress to design level detail, period-of-record procedures (for the

simpler systems) and multiple discrete events for the more complex systems are likely to be found as the appropriate methods.

b. The selection of a strategy for the hydrologic analysis that is efficent and adaptable to the several stages of a specific study is an important step toward obtaining viable results for the study. Due to the uniqueness of each study, the strategy should be custom designed, using analytical methods that are applicable to the study condition, the data, and the flood loss reduction measure assessment requirements.